Prospects for detecting an η'_c

in two photon processes

T. Barnes

Physics Division, Oak Ridge National Laboratory,

Oak Ridge, TN 37831-6373 and

Department of Physics, University of Tennessee,

Knoxville, TN 37996-1501

T.E. Browder and S.F. Tuan

Department of Physics, University of Hawaii at Manoa,

Honolulu, HI 96822

Abstract

We argue that an experimental search for an η'_c, the first radial excitation of the $\eta_c(2980)$, may be carried out using the two photon process $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\eta'_c$. We estimate the partial width $\Gamma_{\gamma\gamma}(\eta'_c)$ and the branching fraction $B(\eta'_c \to h)$, where h is an exclusive hadronic channel, and find that for $h = K^o_s K^\pm \pi^\mp$ it may be possible to observe this state in two photon collisions at CLEO-II.

The η'_c meson is the first radial excitation of the $\eta_c(2980)$, the charmonium ground state with $\mathrm{J^{PC}} = 0^{-+}$. The mass and couplings of this state can be used to test potential models and lattice QCD calculations. In this paper we discuss possible experimental signatures and event rates for the η'_c, and note that it may be observable in future CLEO-II data sets.

The search for the η_c' [1], expected near a mass of 3600 MeV, has intrigued workers in the field for over a decade. In an e^+e^- experiment the Crystal Ball collaboration [1] reported evidence for this state near 3590 MeV, with a branching fraction of $0.2\% < B(\psi' \to \gamma + \eta_c') < 1.3\%$ at 95% confidence level. However the Crystal Ball observation has not been confirmed by subsequent experiments over the intervening 13 years.

Since the relative rates for competing electromagnetic decays and transitions to lower charmonium states are expected to be small for the η_c', the relation [2]

$$B(\eta_c' \to h) \cong B(\eta_c \to h) \ , \tag{1}$$

where h is an exclusive final state, can be assumed as a working hypothesis. Since the $\eta_c(2980)$ branching fractions are known for many hadronic channels [3] we can then estimate event rates for η_c' decays into the same modes.

Of course there are important uncertainties in these estimates; it is well known that the analogue of Eq.(1) for the ψ and ψ' does not account for the puzzling weakness of certain $\psi' \to h$ modes, notably vector+pseudoscalar final states such as $h = \rho\pi$ and $K^*\bar{K} + h.c.$ [3]. In part these small ψ' branching fractions simply reflect the presence of important $\psi' \to \psi + h$ "hadronic cascade" modes, which have a large branching fraction of 57(4)% [3]. We expect these cascade modes to be much less important for the η_c', due to the larger annihilation width of a 0^{-+} state. Of course there remains considerable uncertainty regarding these branching fractions, which merit careful investigation when more data on radial $c\bar{c}$ states becomes available.

For a three-body or four-body hadronic decay mode h, such as those considered here for the η_c', the corresponding QCD-motivated relation $B(\psi' \to h)/B(\psi \to h) \approx 0.13$, discussed by Brodsky et al. [2] appears to be reasonably well satisfied [3], and the recent BES measurement of $B(\psi' \to K^+K^-\pi^+\pi^-)$ is also consistent with this estimate [4].

As a first possibility for observing the η_c' we estimate the number of events expected at BES in the decay chain $\psi' \to \gamma\eta_c' \to \gamma h$, assuming that Eq.(1) is approximately correct. At present there are about $3.4 \times 10^6 \psi'$ events in the BES data set, and the two largest

$\eta_c(2980)$ branching fractions are to $K_s^o K^{\pm} \pi^{\mp} (\cong 1.5 \pm 0.4\%)$ and $\pi^+ \pi^- K^+ K^- (\cong 2^{+0.7}_{-0.6})\%$. Taking the lower end of the range reported by Crystal Ball [1], $B(\psi' \rightarrow \eta_c' + \gamma) = 0.2\%$, we would expect 102 events from the decay $\psi' \rightarrow \gamma \eta_c' \rightarrow \gamma\ h$, $\eta_c' \rightarrow K_s^o K^{\pm} \pi^{\mp}$, and 136 events from the corresponding decay with $\eta_c' \rightarrow \pi^+ \pi^- K^+ K^-$. The average efficiency for detection is approximately 5% with the current BES calorimeter [4] (the photon produced in the radiative transition $\psi' \rightarrow \gamma \eta_c'$ is soft, with an energy of < 90 MeV), so unfortunately the total expected number of events is reduced to 5.1 ± 1.4 and $6.8^{+2.4}_{-2.0}$ respectively. In a missing-γ analysis, in which one does not detect the low-energy γ, the efficiencies are estimated to be 15 - 25% [5], so the number of events expected would be 15.3 ± 4.2 and $20.4^{+7.2}_{-6.0}$ (for 15%) and 25.5 ± 7.0 and $34.0^{+12.0}_{-10.0}$ (for 25%). In view of the small event sample anticipated, success of this approach may require a BES upgrade to a detector similar to the Crystal Barrel or a larger integrated luminosity.

Although the transition $\psi' \rightarrow \gamma \eta_c'$ required to detect the η_c' in this approach has not been observed since the Crystal Ball experiment [1], we note that the branching fraction of 0.2% we used for our estimates is quite conservative; in comparison, Godfrey and Isgur [6] quote a $\langle \psi' | \mu | \eta_c' \rangle$ transition magnetic moment that corresponds to $B(\psi' \rightarrow \gamma \eta_c'(3590)) = 0.8\%$. Of course this branching fraction could be somewhat smaller; it scales as E_γ^3 and roughly as $1/m_c^2$, so a somewhat higher η_c' mass and a larger m_c value than is normally assumed could conceivably reduce the branching fraction to 0.2%.

E835 proposes to search for the η_c' at FERMILAB in the process $p\bar{p} \rightarrow \eta_c' \rightarrow \gamma\gamma$, which requires rejection of a large hadronic background. The preceding experiment, E760, searched for evidence of an η_c' in the mass range 3584-3624 MeV without success. For the η_c, E760 reported $B(\eta_c \rightarrow \gamma\gamma) = (2.80^{+0.67}_{-0.58} \pm 1.0) \times 10^{-4}$ [8]; this is close to a perturbative QCD estimate of $B(\eta_c \rightarrow \gamma\gamma) = 3.0 \times 10^{-4}$ [7], but the signal is seen at a mass of $2988^{+3.3}_{-3.1}$ MeV, somewhat higher than the PDG value of 2978 ± 1.9 MeV. It is especially interesting that E760 finds a rather large width for the η_c, $\Gamma_{\eta_c} = 23.9^{+13.6}_{-7.1}$ MeV, compared to the PDG value of $10.3^{+3.8}_{-3.4}$ MeV. This number is required to convert the E760 $\eta_c \rightarrow \gamma\gamma$ branching fraction

to the theoretically more accessible $\gamma\gamma$ partial width, so until Γ_{η_c} is accurately measured a definitive comparison with theory will not be possible.

Of course the absence of an $\eta_c'(3600)$ signal at E760 may be due to a weak $\eta_c' - p\bar{p}$ coupling relative to $\eta_c - p\bar{p}$, as has been observed in the $\psi' - p\bar{p}$ and $\psi - p\bar{p}$ couplings; the PDG branching fraction $B(\psi' \to p\bar{p})$ is an order of magnitude smaller than $B(\psi \to p\bar{p})$. Although Brodsky and Lepage [9] anticipated a weak coupling of the η_c' to $p\bar{p}$ in perturbative QCD, their results should apply to the ground state η_c as well; the expected weak $\eta_c - p\bar{p}$ coupling is not supported by experiment. Clearly the relative annihilation amplitudes of ground-state and radial quarkonia to exclusive hadronic final states is a vitally important question for these experiments, and it is unfortunately not well understood at present.

From Eq.(1), we expect the η_c' branching fraction ratio $B(\eta_c' \to \gamma\gamma)$ / $B(\eta_c' \to h)$ to be comparable to the $\eta_c(2980)$ ratio. Thus in the absence of a magnetic spectrometer to detect exclusive hadronic modes h, $p\bar{p}$ experiments such as E835 will have to contend with a correspondingly weak signal in the search for the η_c'.

Having discussed searches for the η_c' in $\psi' \to \gamma\eta_c'$ and $p\bar{p} \to \eta_c'$, we now consider a third possibility, the reaction

$$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\eta_c' \; .$$

It is interesting to consider whether this process is likely to lead to an observable signal with present and future data sets. (One of us previously suggested that the χ_{cJ}' (J$= 0, 2$) states expected near 3.95 GeV, the radial excitations of the χ_{cJ} states, could be observed in this manner [10].)

CLEO-II and LEP experiments such as L3 are well equipped to study exclusive hadronic modes h. Indeed, these experiments have confirmed the existence of the ground state $\eta_c(2980)$ in this manner [11–13]. To estimate the number of η_c' events in these $\gamma\gamma$ experiments we again assume the validity Eq.(1); in addition we require a theoretical estimate of the $\Gamma_{\gamma\gamma}(\eta_c')$ partial width.

The partial width $\Gamma_{\gamma\gamma}(\eta_c'(3590))$ has been calculated by Ackleh and Barnes [14] using

nonrelativistic quark potential model wavefunctions attached to relativistic Feynman decay amplitudes; this gives $\Gamma_{\gamma\gamma}(\eta_c'(3590)) = 3.7$ keV. For comparison, this approach applied to the η_c gave the prediction

$$\Gamma_{\gamma\gamma}^{thy.}(\eta_c) = 4.8 \text{ keV} , \tag{2}$$

which is consistent with recent E760, CLEO-II and L3 measurements;

$$\Gamma_{\gamma\gamma}^{expt.}(\eta_c) = \begin{cases} 6.7^{+2.4}_{-1.7} \pm 2.3 \text{ keV} & \text{E760 [8]} \\ 4.3 \pm 1.0 \pm 0.7 \pm 1.4 \text{ keV} & \text{CLEO [12]} \\ 8.0 \pm 2.3 \pm 2.4 \text{ keV} & \text{L3 [13] .} \end{cases} \tag{3}$$

(The E760 reference gives a more complete summary of previous experimental results, in their Table V.)

An important conclusion of Ackleh and Barnes is that $\Gamma_{\gamma\gamma}$ widths of quarkonia are not strongly suppressed with radial excitation for light *or* heavy quarks. This suggests that a radially excited $\eta_c'(\approx 3600)$ may be observable in $\gamma\gamma$ collisions, provided that the exclusive hadronic channel studied does not have an unusually weak coupling to the η_c'.

The level of uncertainty in the η_c' $\gamma\gamma$ width in the model of Ackleh and Barnes can be estimated by considering a likely range of $M(\eta_c')$ values, and allowing plausible variations in the three model parameters. The effect of varying $M(\eta_c')$ over the range 3590 ± 50 MeV is to change $\Gamma_{\gamma\gamma}(\eta_c')$ by ± 0.15 keV, a $\pm 4\%$ change. Variations in the three parameters α_s, b (GeV/fm), and m_c have also been considered. The effect of varying the first two is quite small; the width is most sensitive to the charm quark mass m_c, which was taken to be 1.4 GeV in Ref. [14] and our Eq.(2). As we increase m_c from 1.3 to 1.8 GeV, $\Gamma_{\gamma\gamma}(\eta_c')$ decreases monotonically by about a factor of two. Fortunately, $\Gamma_{\gamma\gamma}(\eta_c')$ and $\Gamma_{\gamma\gamma}(\eta_c)$ show similar m_c dependences, so the ratio $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c)$ only changes from 0.73 to 0.77. Comparison with the experimental η_c values then supports our use of $\Gamma_{\gamma\gamma}(\eta_c') = 3.7$ keV as a reasonable first estimate in determining numbers of events. It should be noted however that no radial excitations have yet been identified in $\gamma\gamma$ collisions, so this width calculation is a theoretical estimate in a regime in which the theory has not been tested.

In two photon physics the number of events is related to the production cross section in e^+e^- by [11]

$$N_{obs} = \epsilon \, L \, B(R_{c\bar{c}} \to F_s) \, \sigma_{exp}(e^+e^- \to e^+e^- R_{c\bar{c}}) \; , \qquad (4)$$

where ϵ is the efficiency for detecting the final state F_s, $B(R_{c\bar{c}} \to F_s)$ is the branching fraction for $R_{c\bar{c}}$ into F_s, L is the luminosity, and N_{obs} is the number of $R_{c\bar{c}} \to F_s$ events observed. Here we specialize to $R_{c\bar{c}} = \eta_c(2980), R'_{c\bar{c}} = \eta'_c(3590), F_s$ an exclusive final state h, and the luminosities are L and L' respectively. The ratio of the number of events N'_{obs} expected for an $\eta'_c(3590)$ to the $\eta_c(2980)$ number is then

$$\frac{N'_{obs}}{N_{obs}} = \frac{\epsilon' L'}{\epsilon L} \, \frac{B(\eta'_c \to F_s)}{B(\eta_c \to F_s)} \, \frac{\Gamma_{\gamma\gamma}(\eta'_c)}{\Gamma_{\gamma\gamma}(\eta_c)} \; , \qquad (5)$$

where we have taken the ratio of $\gamma\gamma$ production cross sections for an η'_c and the $\eta_c(2980)$ to be the ratio of their respective $\gamma\gamma$ widths, up to photon flux factors [15].

For the photon flux factors we have $L'/L = 1/2.02$ [16]. Since we assume Eq.(1) it follows that $\epsilon' = \epsilon$, i.e. the detection efficiencies are equal because the final states are identical. (We assume that the difference in invariant mass of the two states has no significant effect on the efficiency.) From the theoretical estimate above we have $\Gamma_{\gamma\gamma}(\eta'_c)/\Gamma_{\gamma\gamma}(\eta_c) \approx 1/1.3$. Using the yield $N_{obs} = 54.1 \pm 12.6$ events for $h = K_s^o K^\pm \pi^\mp$ reported by CLEO-II for the η_c, (c.f. Savinov and Fulton in ref. [12]), we obtain $N'_{obs} \cong 20.6 \pm 4.8$ for the η'_c. Note the large number of exclusive events expected at CLEO-II, in contrast with LEP experiment L3, for which the corresponding N_{obs} for $\eta_c \to K_s^o K^\pm \pi^\mp$ is 3 events [13]. The difference is primarily due to the smaller integrated luminosity available at the LEP experiments.

It would be useful for CLEO-II to extend their search to include $\eta'_c \to \pi^+\pi^- K^+K^-$, which is also expected to have a large branching ratio ($\sim 2\%$ according to Eq.(1)). Of course the CLEO-II detector (now at the CESR e^+e^- storage ring, and running at a center-of-mass energy near the $\Upsilon(4S)$, ≈ 10.6 GeV), is continually accumulating data, so prospects for finding the η'_c will improve with time. The value of N'_{obs} estimated above assumes a dataset with an integrated luminosity of 3.0 fb^{-1}, and should be scaled with the size of the dataset. It

is anticipated for example that the CLEO dataset will have an integrated luminosity of about 10.0 fb^{-1} by 1998 [17], so our expected number of η'_c events would then be $N'_{obs} = 68.7 \pm 16.0$.

In summary, we have considered some possible experimental signatures for η'_c production, and suggest that $e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-\eta'_c$, $\eta'_c \rightarrow K^0_s K^\pm \pi^\mp$ may be feasible at CLEO-II. Searches for the η'_c in this process can be conducted at CLEO-II, LEP, and future B factories.

REFERENCES

[1] C. Edwards et al., Phys. Rev. Lett. 48 (1982) 70.

[2] K.T. Chao (Zhao), Y.F. Gu, and S.F. Tuan, "On Trigluonia in Charmonium Physics", BIHEP-TH-93-45, PUTP-93-24, and UH-511-790-94; Commun. Theor. Phys. (in press); S.J. Brodsky, G. Peter Lepage, and S.F. Tuan, Phys. Rev. Lett. 59, 621 (1987); S.F. Tuan, "Aspects of Charmonium", UH-511-832-95, hep-ph/9509388; Proceedings of the HADRON'95 conference (in press).

[3] Review of Particle Properties, Phys. Rev. D50, Part I (August 1994).

[4] Y.F. Gu (BES Collaboration), private communication.

[5] Y.F. Gu and S. Olsen (BES Collaboration), private communication.

[6] S. Godfrey and N. Isgur, Phys. Rev. D32, 189 (1985).

[7] R. Cester and P.A. Lapidis, "Charmonium Formation in $p\bar{p}$ Annihilations", FERMILAB Pub-94/123, May 1994, to appear in Annual Review of Nuclear Sciences; W. Kwong et al., Phys. Rev. D37, 3210 (1988).

[8] T.A. Armstrong et al., Phys. Rev. D52 (1995) 4839.

[9] S. J. Brodsky and G. P. Lepage, Phys. Rev. D24, 2848 (1981).

[10] S.F. Tuan, PRAMANA, Vol. 45, No.2, August 1995, pp. 209-214. By a proper inclusion of the photon flux factors, the cross section ratio in Eq.(18) of this reference is equal to $0.65 \times \Gamma_{\gamma\gamma}(\chi'_{c2})/\Gamma_{\gamma\gamma}(\chi_{c2})$, where the photon flux factor is given for instance in ref. [15] below.

[11] R. Fulton, "Two-Photon Production of Charmonium States", Ph.D Thesis, The Ohio State University (1995).

[12] V. Savinov and R. Fulton (CLEO-II Collaboration), Contribution to the PHOTON95

conference, Sheffield (1995).

[13] O. Adriani et al., Phys. Lett. B 318 (1993) 575.

[14] E.S. Ackleh and T. Barnes, Phys. Rev. D45 (1992) 232; C.R.Münz, Bonn University report TK-96-01, hep-ph/9601206, uses a Bethe-Salpeter formalism to estimate these widths and finds a somewhat smaller $\Gamma_{\gamma\gamma}(\eta_c'(3590)) = 1.38(30)$ keV. This references summarizes other predictions, which lie in the range $\approx$ 1.0-1.7 keV, somewhat smaller than the result of Ackleh and Barnes.

[15] R.N. Cahn, Proceedings of the XIVth International Symposium on Lepton and Photon Interactions, Stanford (1989) p. 60; particularly Eq. (12.1).

[16] Monte Carlo integration of the exact differential cross section without assuming the equivalent photon approximation gives 2.32 rather than 2.02 for the ratio of photon flux factors. This would reduce the event yield by about 15%. Private communication, Vladimir Savinov.

[17] K. Berkelman, Cornell preprint CLNS 96/1396.